Radial Transport and Electron-Cyclotron-Current Drive in the TCV and DIII-D Tokamaks

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Calculation of electron-cyclotron-current drive (ECCD) with the comprehensive CQL3D Fokker-Planck code for a TCV tokamak shot gives 550 kA of driven toroidal current, in marked disagreement with the 100-kA experimental value. Published ECCD efficiencies calculated with CQL3D in the much larger, higher-confinement DIII-D tokamak are in excellent agreement with experiment. The disagreement is resolved by including in the calculations electrostatic-type radial transport at levels given by global energy confinement in tokamaks. The radial transport of energy and toroidal current are in agreement.

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Electron cyclotron current drive (ECCD) is expected to play an important role in sustaining the toroidal current profile and suppressing instability in high performance tokamaks. Computational tools, such as the CQL3D Fokker-Planck code [1], have been widely applied to predict and interpret experiments. Agreement between experiments on the DIII-D tokamak (minor radius $a = 0.6$ m, major radius $R_0 = 1.7$ m, EC power $P_{EC} = 1.5$ MW) and no-free-parameter calculations of driven current has been very good [2], usually within 15%, and supports the assertion that EC absorption and current drive are well understood. But recent experiments by the TCV tokamak ($a = 0.25$ m, $R_0 = 0.9$ m, $P_{EC} = 1.5$ MW) which showed for the first time full, steady-state sustainment of the plasma current by ECCD [3] have markedly disagreed with the same theory. We show that agreement between calculations and experiment in both devices is obtained by including in the calculations a reasonable model of radial transport at a level consistent with the global energy confinement of the International Tokamak Experimental Reactor (ITER) [4] data base studies.

The role of radial transport on high energy electrons, particularly regarding radiofrequency (rf) experiments, has been examined extensively ([5–11], and references therein). Unique features in this Letter are that the TCV tokamak is entirely driven by EC power, removing ambiguities of Ohmic current and runaway electron current, and that the CQL3D numerical model for EC absorption and current drive has been extensively benchmarked against the well-diagnosed DIII-D tokamak. The transport effect in TCV is overwhelming, reducing computed rf current from 550 to the 100 kA experimental value.

As the magnitude of rf power is increased in tokamaks, the radial diffusion time decreases in accord with the inverse dependence of global confinement on heating power. At the same time the electron temperature increases, which increases the velocity and hence the collisional scattering time for electrons. The current drive physics depends on whether the diffusion time is shorter or longer than the scattering time. In the high power TCV experiment, the radial transport time is shorter than the collisional scattering time for a substantial fraction of the ECCD currrent carriers.

Although there is little doubt that plasma turbulence is responsible for the observed radial transport in excess of collisional levels [4], there remains uncertainty about whether electrostatic (ES) or magnetic turbulence dominates [12–15] and about the effects on toroidal current. We show good agreement between experiment and modeling based on radial diffusion due to ES-type turbulence which is constant in velocity space at a level predicted by well-known empirical modeling of tokamaks; we show poor agreement with a purely magnetic turbulence-type radial diffusion coefficient modeled here as proportional to the parallel velocity of the electrons [13,14], although mixed ES, magnetic, and nonlinear effects could bring in other velocity dependences [14,15].

The calculations are performed with the comprehensive CQL3D Fokker-Planck/Quasilinear (FP/QL) simulation code [1]. This model uses a collisional diffusion operator which is two-dimensional in momentum space, the full Stix [16] rf QL diffusion coefficient, a radial diffusion D_{rr} and pinch term in noncircular flux surface geometry, and is relativistic. The pinch term is adjusted to maintain a target experimental density profile. Steady-state, finite-difference numerical solutions of the bounce-averaged FP equation are obtained for the electron distribution $f_e(u, \theta, \rho)$ evaluated at the outer equatorial plane of the toroidal plasma, where $u = p/m_e$ is momentum-per-electron-rest-mass, θ is momentum space pitch angle, and ρ is a normalized radial coordinate labeling the toroidal flux surfaces. The radial diffusion may be chosen as an arbitrary function of velocity and radius. For the TCV modeling, the velocity dependence of D_{rr} is chosen as either constant to simulate ES turbulence or proportional to the magnitude of the electron velocity parallel to the ambient magnetic field normalized by thermal velocity $|v_{\|}|/v_{\mathrm{Te}}$ to simulate magnetic turbulence, where $v_{\mathrm{Te}} = [\mathrm{T_e}(\rho)/m_{\mathrm{e}}]^{1/2}$. D_{rr} increases towards the plasma periphery, $D_{rr} = D_{rr0}[1 + 3\rho^3][n_{e0}/n_e(\rho)]$, in general accord with experimental observations for the relevant low confinement L-mode [17]. The EC radiation field is obtained from data coupled into CQL3D from the TORAY-GA

[18] ray tracing code with damping calculated self-consistent with the distribution functions. We expect that, using the experimentally measured profiles of plasma density (n_e), temperature (T_e), and effective charge ($Z_{\rm eff}$), the CQL3D code provides a full and accurate physics-based model of the ECCD process in tokamaks, apart from the radial transport effects which are implemented empirically.

The experiments on TCV and DIII-D are very similar: central plasma densities (n_{e0}) and temperatures (T_{e0}) and magnetic field strength (B) are comparable ($n_{e0} = 1.25/2.0 \cdot 10^{13}$ cm^{-3}, $T_{e0} = 3.3/2.7$ keV, $B = 1.4/2.0$ T in TCV/DIII-D); the lower density in TCV is offset by higher $Z_{\rm eff} = 5$ compared to the DIII-D $Z_{\rm eff} = 1.4$. Approximately 1.5 MW of X-mode EC radiation is injected from the off-midplane outboard sides of the tokamaks [2,3] to resonate with plasma electrons near the second-harmonic of the cyclotron frequency. The major difference between the two tokamaks is that DIII-D is 15 times the volume of TCV giving much higher EC power density in TCV. Both the TCV and DIII-D tokamaks provided data to the nine tokamak data base from which the ITER empirical L-mode scaling is derived [4]. It is plausible that the transport discussed below is governed by the same general turbulence processes in each of the tokamaks.

We examine the TCV shot 16099 which is fully supported by EC power [3] with ray geometry as shown in Fig. 1. Distributing the radial locations of the 1.5 MW of EC heating and CD as shown in the figure was found by the authors of Ref. [3] to be required to obtain a kink stable, marginally sawtoothing, 100 kA discharge.

The ECCD in TCV calculated by CQL3D without including radial diffusion is 550 kA, more than 5 times the experimentally measured value. Figure 2 shows the calculated driven EC current as a function of the central radial diffusion coefficient D_{rr0} used in the simulation, for the two velocity dependences: ES-type and magnetic-type. The observed EC driven current is obtained for the electrostatic-type diffusion with $D_{rr0} \approx 3.7$ m^2/s, whereas for the magnetic-type diffusion the value is 0.35 m^2/s.

The magnitude of the diffusion coefficient obtained above is in excellent agreement with the ITER L-mode scaling [4],

$$\tau^L_{E,\rm th} = 0.023 I^{0.96} B^{0.03} P^{-0.73} n^{0.40} \times M^{-0.20} R^{1.183} \epsilon^{-0.06} \kappa^{0.64},$$

(s, MA, T, MW, 10^{19} m^{-3}, AMU, m). Applied to TCV shot No. 16099, this gives confinement time 2.5 ms, close to the experimentally determined value 2.1 ms [3]. Transforming this to an estimate of the radial diffusion coefficient using $D_{rr0} = 0.5\ \mathrm{a}^2/4\tau^L_{E,th}$ (the factor 0.5 accounts approximately for the radial dependence of D_{rr}) gives $D_{rr0} = 3.0$ m^2/s. The confinement time for this shot is in reasonable agreement with $\tau_{E,th}$ scaling studies of TCV obtained over a broad range of ECCD shots [19]. If the magnetic-type diffusion coefficient were increased sufficiently to fit the bulk transport, it would be 10 times too strong for the code to match the observed ECCD, providing strong support for ES turbulence, not magnetic turbulence, dominating both bulk and tail electron transport.

Further insight into the dependence of the ECCD on D_{rr0} can be obtained from CQL3D results. The top of Fig. 3 shows cuts at constant pitch angle through the electron distribution for plasma radius 0.1 a; below them are the corresponding distributions $j_u(u)$ of driven current versus u normalized to the thermal velocity, such that current density $j = \int j_u(u)\, du$. Case (a) is with no radial diffusion and case (b) is with ES radial diffusion coefficient of 3.7 m^2/s. The lower-u portion of the distributions remains Maxwellian at the given experimental temperature. Without radial diffusion a large current-carrying tail to the distribution is formed out to near the edge of the mesh. The effect of the transport is to sharply reduce the driven electron current to the 100 kA experimental value. This value is slightly above the 82 kA obtained linearly

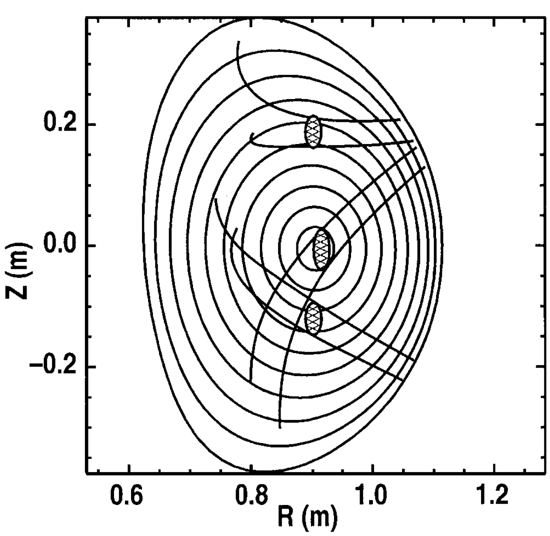

FIG. 1. Cross section of toroidal plasma in TCV showing ray cones and heating regions for shot No. 16099.

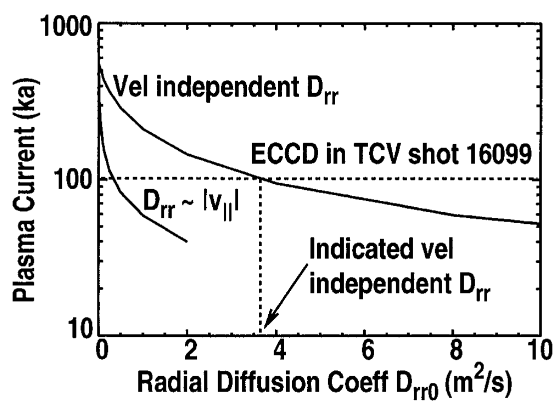

FIG. 2. Calculated EC driven plasma current in TCV as a function of the radial diffusion coefficient.

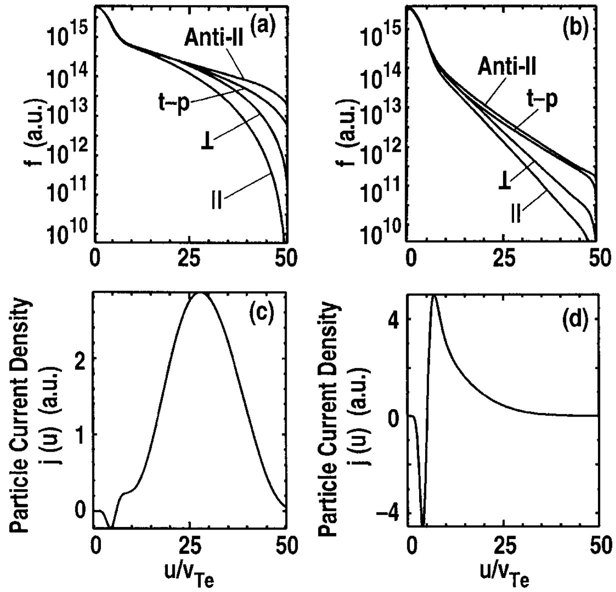

FIG. 3. Left column (a) shows cuts through the distribution as a function of u, at various pitch angles from the co- to the counter-direction of the electron current drive; below is the distribution $j_u(u)$ of driven current, resulting from ECCD in TCV with no radial diffusion. The right column (b) is the same, but calculated with radial diffusion turned on.

with CQL3D by evaluating CD at a very low power in the absence of D_{rr} and renormalizing back to the experimental power. The CQL3D linear value is slightly greater than the 70 kA from the TORAY-GA code, based on the Cohen [20] model which neglects current excited in the thermal portion of the electron distribution by the electron-electron collisions. Thus, diffusion using the ES turbulence model with a magnitude consistent with the bulk transport in TCV reduces the ECCD to a value marginally in excess of the TORAY-GA calculation, in agreement with results reported in Refs. [3] and [19]. The resulting radial current profiles are shown in Fig. 4. The central value of current density $j(\rho = 0)$ has been reduced to a value giving safety factor $q = 1.0$, in agreement with the experimentally reconstructed equilibrium [3], and in support of the chosen radial variation of D_{rr}.

The multichannel hard x-ray diagnostic system [21] on TCV provides additional information [22]. The calculated tail x-ray temperatures are reduced by a factor of 2 by transport at levels giving 100 kA ECCD (24 keV for ES, 22 keV for magnetic), in general agreement with the experiment. Tail temperature at photon energy greater than 30 keV is insensitive to the minor radius tangency ρ_{XR} of the x-ray sightline but the flux decreases by an order of magnitude as ρ_{XR} varies from 0.0 to $0.8a$, similar to the Ohmic transport case [13].

Experiments have corroborated the ability of CQL3D to predict ECCD efficiency in DIII-D [2], with no radial transport in the code. A scan of D_{rr0} from 0 to 4.0 $\mathrm{m^2/s}$ using the ES model indicates that the ECCD (including synergy with the induced toroidal electric field) is only reduced from 45.1 to 40.0 kA, for a benchmark

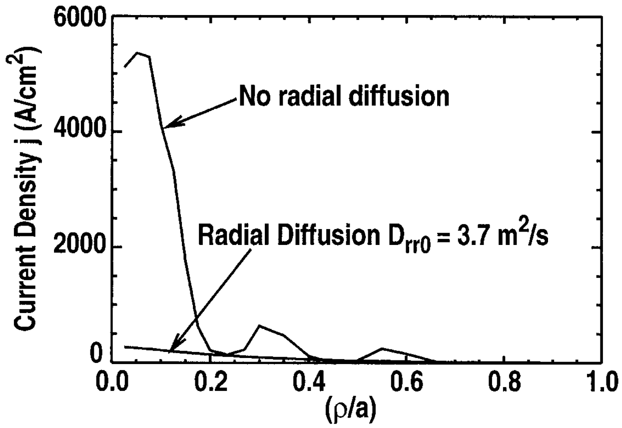

FIG. 4. Calculated radial profile of current density in TCV, with and without radial diffusion.

shot (#104017). This change in current is within the experimental uncertainty. The value $D_{rr0} = 2.0\ \mathrm{m^2/s}$ is obtained from the ITER L-mode $\tau^L_{E,th}$ scaling for this shot. Figure 5 gives calculated radial current density profiles. The ECCD efficiency is not appreciably changed, but spreading of the driven EC current occurs which should be considered for stabilization of neoclassical tearing modes [23,24].

Further clarification of why radial transport is not crucial in present DIII-D experiments but is crucial in TCV experiments is shown in Fig. 6 where collisional deflection time $\tau^e_\perp = 9.1 \cdot 10^{-6} \mathrm{T}^{3/2}_{\mathrm{keV}} (v/v_{\mathrm{Te}})^3/[(1 + Z_{\mathrm{eff}})n_{13}]$ (s) is plotted versus tail electron velocity v/v_{Te}. Approximately common values for the TCV and DIII-D discharges, $T_{\mathrm{keV}} = 2.5$, collisional factor $n_{13}(1 + Z_{\mathrm{eff}}) = 4.0$, are assumed. Near the top of this figure at the level of the energy confinement time $\tau_{E,th}$ for diffusion across the radius $\delta\rho = a$ in DIII-D, the horizontal line indicates the range of nonthermal particles from CQL3D simulations with no radial transport; since this confinement time is large compared to $\tau^e_\perp(v)$, no appreciable global effects appear on the CD. Next, in the center of the plot, the TCV energy

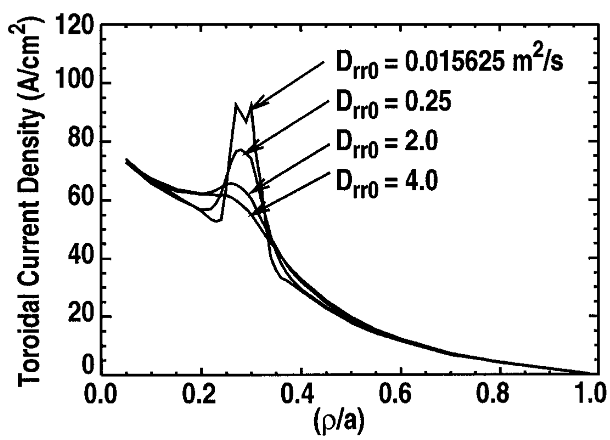

FIG. 5. Calculated radial profile of current density in the DIII-D experiment, shot No. 104017, for various levels of radial diffusion. $D_{rr} = 2.0\ \mathrm{m^2/s}$ matches the ITER L-mode scaling.

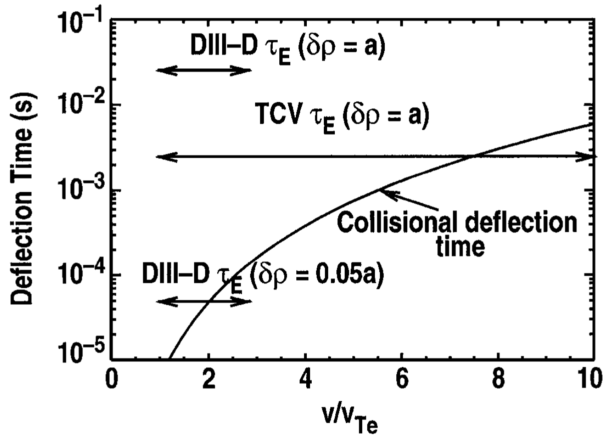

FIG. 6. Collisional deflection time is plotted versus tail electron velocity normalized to the thermal velocity, applicable for both TCV and DIII-D shots. Also shown on the plot are transport times for DIII-D and TCV, and the regions of appreciable nonthermal electrons excited by the ECH.

confinement time is less than $\tau_\perp^e$ for high velocity tail particles, so transport enters strongly in the physics of CD. Finally, towards the bottom of Fig. 6, the confinement time for electrons within the small radial range of ECCD in DIII-D (half-width $\delta\rho = 0.05a$) is shown. Again, $\tau_{E,th}$ is significantly less that $\tau_\perp^e$, and radial transport can lead to important spreading of the driven current.

The TCV power densities in the regions of rf deposition exceed the criterion for substantial nonlinear enhancement of CD given in Harvey *et al.* [25] by a factor of 20 centrally to 4 at radius $0.55a$, as in our calculations without transport. For DIII-D, the criteria is exceeded by 1.3.

To conclude, we have shown for the TCV and DIII-D experiments that the calculation of the radial transport effects at levels predicted by the ITER data base brings the experimental observations of ECCD into agreement with accepted electron cyclotron current drive physics. We are confident that CQL3D can predict ECH power density and ECCD profiles for next step machines such as ITER. The transport effect is strongly dominant in the high power density TCV, and future studies in this machine with its powerful, flexible ECH system, will reveal more details of radial plasma confinement of electrons. The TCV results are consistent with electrostatic-type turbulence but not a purely magnetic turbulence. Tail current diffuses radially consistent with energy transport.

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